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CLIMATE CHANGE IN THE LAST CENTURY AND ITS IMPACT ON WATER CYCLE IN CENTRAL ASIAN ARIDZONE

ABSTRACT

Arid regions are home to more than 40 % of the total global population and are one of the most sensitive areas to climate change and human activities. As the largest arid region over the north hemisphere, Central Asia has experienced the significant increasing rate of the surface temperature during the late century, especially during the recent decades (1979-2011). According to the analysis of multiple datasets, no significant contributions from declining irrigation and urbanization to temperature change were found. A warming center in the middle of the central Asian states and weakened temperature variability along the northwest–southeast temperature gradient from the northern Kazakhstan to southern Xinjiang. An overall increasing trend of the annual precipitation was found over this region in the last century. Furthermore, the annual precipitation exhibited high-frequency variations and low-frequency variations. There exist significant differences of the precipitation between the mountainous areas and plain areas. The research of the ecosystem variations and their responses to the climate change are important and urgent over the arid regions. The development of the remote sensing technologies provide a possible approach to address the above problems. Climate change and the ecosystem variations should be explored together to reveal the rules of the climate system and ecosystem as a whole according to the traditional climate methods and the new remote sensing means.

KEYWORDS:

climate change, remote sensing, aridzone, ecosystem

INTRODUCTION

Climate change is a change in the climate state that can be identified (e.g., by using statistical tests or climate models) by changes in the mean and/or the variability of its properties and that persists for an extended period (IPCC 2012). It can have great impacts on glaciers [Gardner *et al.*, 2011; Sorg *et al.*, 2012], water cycle [Grover, 2014], agriculture [Piao *et al.*, 2010] and human health [Patz *et al.*, 2005] over regional and global scales. Furthermore, the changes in the frequency or intensity of extreme weather and climate events would have greater impacts on both human society and natural systems than the mean climate variables [IPCC, 2012].

The arid regions account for 40 % of global terrain area which have high temperature, little precipitation, lack of water resources and fragile ecosystem [Reynolds *et al.*, 2007]. Therefore, the arid regions are one of the most sensitive areas to climate change and human activities [Reynolds, *et al.*, 2007; Huang *et al.*, 2016]. The Fifth Coupled Model Intercomparison Project (CMIP5) has underestimated the arid region's expansion considering the past 58 years (1948-2005) [Feng, Fu, 2013]. Using historical data to bias-correct CMIP5 projections, an increase in dryland expansion rate resulting in the drylands covering half of the global land surface by the end of 20th century. Moreover, the increasing aridity, enhanced warming and rapidly growing human population will exacerbate the risk of the land degradation and desertification in the near future in the drylands of developing countries [Huang *et al.*, 2016].

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As the largest arid region over the north hemisphere, Central Asia covers an vast area of 5×10^6 km^2, including Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan and Xinjiang Uyghur Autonomous Region in northwest China [Hu *et al.*, 2014; Hu *et al.*, 2016]. This arid and semiarid region expands from 34.3 to 55.4°N and from 46.5 to 96.4°E. It is located in the hinterland of the Eurasian continent, and is primarily dominated by the westerly winds [Chen, Zhou, 2015; Hu *et al.*, 2017]. The complex topography in this region differentiates spatially and temporally the arid/semiarid climate which has the complexity precipitation climate in this region [Chen, Zhou, 2015]. Practically, the western and north-western plains of Central Asia are open to cold northerly and north-westerly inflows as well as to moist westerly Atlantic air masses [Hu *et al.*, 2017]. To the south and east, the Himalayan, Pamir, Hindukush, and Tianshan mountains completely isolate Central Asia from moist air masses from the Indian Ocean [Chen, Zhou, 2015].

CURRENT METHODS OF CLIMATE CHANGES OVER ARID REGIONS

Datasets form the most important basis for the analysis of climate change. During the last century, the original meteorological stations, RADAR and remote sensing satellites provide enormous and highly accurate datasets, including weather measurements such as temperature, precipitation, wind, evaporation and humidity. The measurements provide important information to the better understanding of the climate variations and climate change [Houghton *et al*., 2001; Boe *et al.*, 2009; Chung *et al.*, 2014).

Among numerous climate change issues, the majority of the research has been focused on the mean states, change rates, oscillations, characteristics of abrupt changes, multi-periods, chaos and much more complex dynamical behaviors of the climate systems, using statistical methods [e.g. least square method, ensemble empirical mode decomposition (EEMD), artificial neural networks (ANN) and the empirical orthogonal function (EOF)] and climate models [e.g. global climate models (GCM) and regional climate models (RCM)] at the regional and global scales [Aizen *et al.*, 2001; Ambaum *et al.*, 2001; Balashova *et al.*, 2004; Bintanja, Selten, 2014; Hu *et al.*, 2014, 2017]. Since the aridland ecosystems are understood sensitive to the climate change, the investigation on the spatio-temporal variations of climate change and the ecosystem responses to such change have drawn greater research interests in recent years.

The Intergovernmental Panel on Climate Change [IPCC; Houghton *et al.*, 2001] reported that the average near-surface air temperature in Central Asia has risen by 1–2°C in the last century. However, the report provided no specific information about its temporal (e.g., the time of abrupt temperature changes) or spatial (e.g., areas of substantial temperature rise or fall) variations. Climate Research Unit (CRU) dataset shows that there has been a significant increasing trend for the temperature (0.15°C per decade, $p<0.05$) [Hu *et al.*, 2014] in the region. In the past 33 years (1979–2011), the analysis of multiple datasets revealed significant regional surface air temperature rise of 0.36-0.42°C per decade, which stood out as the highest rate than the surrounding regions [Hu *et al.*, 2014]. For the last half century (1960–2011), the highest increase of surface temperature was observed in the winter season. This was, however, changed in the recent 3 decades (1979-2011) as the high temperature rising season shifted to spring. Spatially, a warming center was found in the middle of the Central Asian states and it weakened the temperature gradient from the northern Kazakhstan (northwest) to southern Xinjiang (southeast). A research also reported that the irrigation and urbanization had no significant impacts on the temperature change according to the records from the meteorology stations [Hu *et al.*, 2014].

Unlike the uniform rising temperature around the globe, the instrumental records and climate model outputs show more complex spatial and temporal variations in precipitation [Boe *et al.*, 2009; Chung *et al.*, 2014]. During the last century, the ecosystem in this region has suffered from serious consequences of environmental change, such as the retreat of glaciers in the Tianshan Mountains [Sorg *et al.*, 2012] and the dry up of the Aral Sea [Micklin, 1988; Fairless, 2007]. The variations and changes of precipitation over Central Asia display more complex spatial and dynamical behaviors than those of the temperature because of its complex topography and climate system [Hu *et al.*, 2016]. However, the records from the meteorology stations alone is insufficient to describe the true pattern of the precipitation over the region with large spatial heterogeneity. Therefore, gridded datasets generated from analytical models and satellite remote sensing should be used to detect the spatiotemporal patterns over Central Asia [Guo *et al.*, 2015; Hu *et al.*, 2016].

Precipitation datasets generated by spatial interpolation and remote sensing have high accuracy compared with the observations from ground stations, although they might underestimate the precipitation over mountainous areas [Hu *et al.*, 2016]. For the last century, there was a mild increasing trend (0.66mm per decade) for the annual precipitation over the entire Central Asia according to the latest version of Global Precipitation Climatology Centre (GPCC) full data reanalysis version 7 (GPCC V7) dataset [Hu *et al.*, 2017]. Multi-periods (3–6 year quasi-periods) are detected by the EEMD method (Hu *et al.*, 2017]. Spatial distributions of the change rates show that opposite change rates are found between CAS5 and Xinjiang during the last century. Moreover, the dominant mode of interannual variability in Central Asia annual precipitation is related to El Niño-Southern Oscillation [Hu *et al.*, 2017].

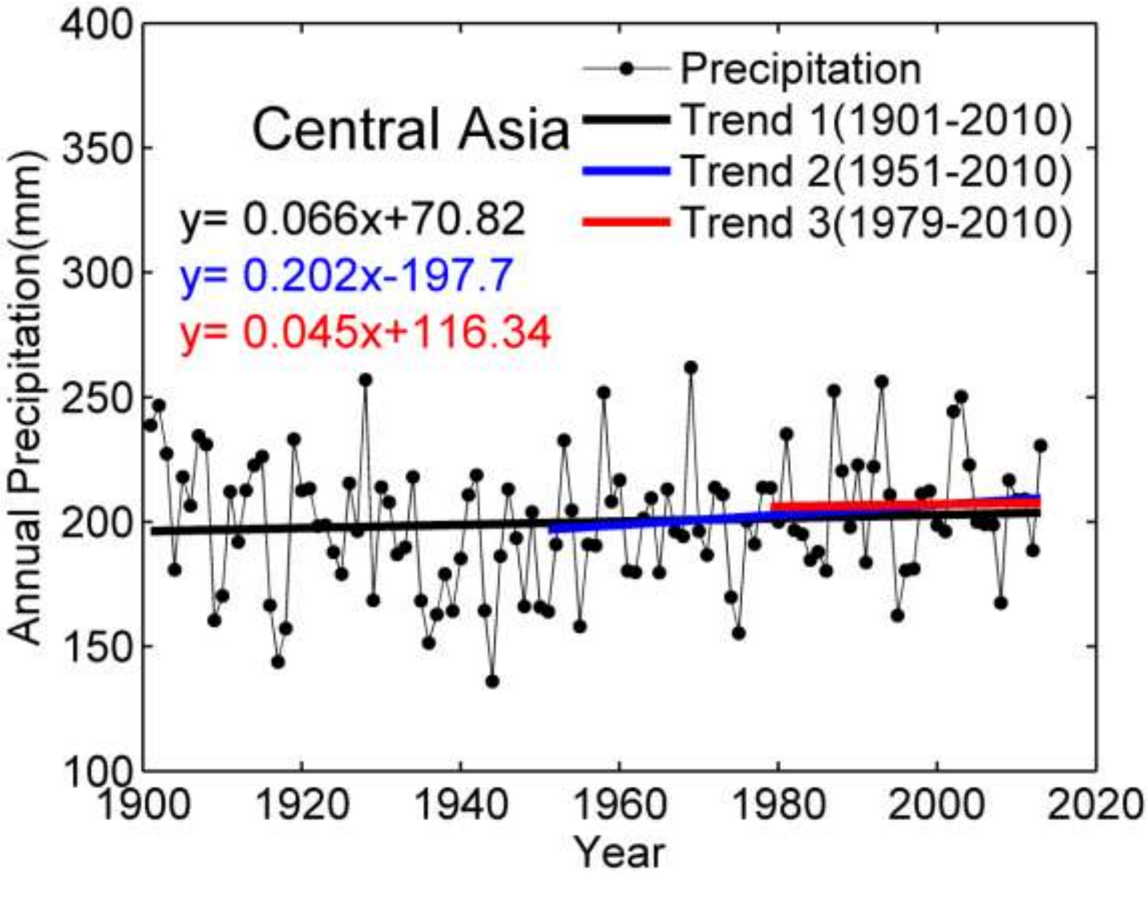

Figure 1. *Linear trend of annual precipitation over Central Asia during 1901-2013 [Hu* et al.*, 2017]*

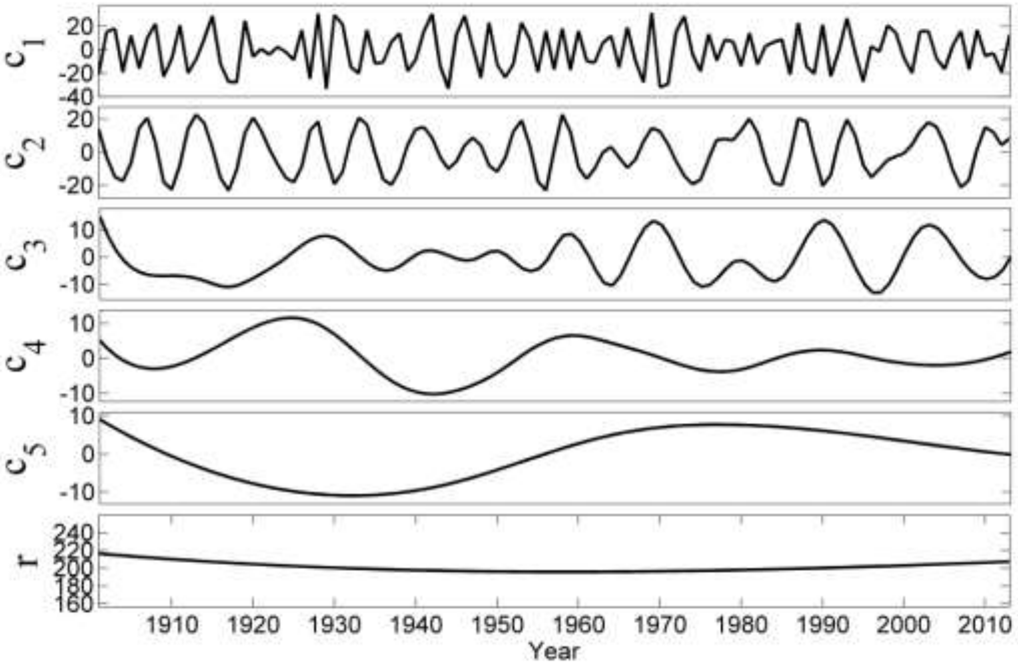

Figure 2. *The decomposition results of annual precipitation time series over Central Asia during the period of 1901–2013 by the EEMD method [Hu* et al., *2013]*

REMOTE SENSING MONITORING METHOD AND SYSTEM FOR THE RESPONSE OF ECOSYSTEM TO CLIMATE CHANGE

Remote sensing technology, which offers various high quality spatial data to allow regular observations over a large region, provides new opportunities for the development of distributed hydrological and land-surface model. Most constituent variables in the land surface water balance (e.g. precipitation, evapotranspiration, snow and ice, soil moisture, and terrestrial water storage variations) are now observable using remote sensing technology with various spatial and temporal resolutions [Tang *et al.*, 2009].

Remote sensing change detection techniques, as it encompasses the quantification of spatio-temporal phenomena from multi-temporal imagery, are commonly adopted in environmental modeling studies [Coppin *et al.*, 2004], particularly for the study of landuse/land cover change. To investigate the spatio-temporal water cycle variations, it is essential to observe numerous environmental variables in frequent time intervals over a large region. The state-of-the-art space-borne remote sensors and advanced change detection techniques provide a solid technological foundation for this study. While imaging satellite techniques and satellite altimetry give access to surface water and superficial soil moisture variations, it represents just the more accessible components of total water storage.

Water resources can be present as glaciers and snow water, surface water, soil moisture and groundwater. However, the scarcity of in-situ measurement site in the study area limits the understanding of the water cycle variation in the study area. Traditional monitoring of terrestrial hydrology relies on costly and time-consuming field data logging and model simulations [Jiang *et al.*, 2014]. Research projects have been undertaken on aridzone water cycle modelling using field data measurements. For example, Li *et al.* [2010] analysed the long-term change of climate and stream flow at the headwaters of Urumqi River using the data at 3 hydro-meteorological stations. However, some hydrological parameters, such as water storage in glacier, remain hardly measurable. Some studies performed extrapolation method for ground hydro-meteorological data [Ling *et al.*, 2011].

Although the spatial accuracy was acceptable for investigation at the basin scale, the result and insight offered were limited for individual basins. For the investigation of spatio-temporal change of water cycle, the traditional in-situ measurement is widely recognized ineffective.

The terrestrial water cycle describes the continuous movement of water on, above, and below the surface of the earth. It is often difficult to quantify the total terrestrial water storage (ice, snow, surface waters, soil moisture, and groundwater) by the traditional field measurements, as available data in arid endorheic river basins are typically limited in terms of extent and quality. In fact, these observations will not provide water cycle closure due to sampling and retrieval errors [Margulis *et al.*, 2006]. Launched in March 2002, the Gravity Recovery and Climate Experiment (GRACE) can provide an operational product in the form of global gravity fields every 30 days [Tapley *et al.*, 2004]. Compared to imagery remote sensing methods, they provide alternative for the estimation of spatial and temporal distribution of vertically integrated sum water storage in the terrestrial hydrological system, particularly for large-scale monitoring of terrestrial water cycle [Jiang *et al.*, 2014].

The data that can be used to monitor the ecosystem responses include remotely-sensed data sets such as GRACE data (since 2002), MODIS and Landsat TM/ETM+/OLI imagery (since 1990), as well as the derivative data such as MODIS snow cover products. Furthermore, precipitation measurements are also derived by the inversion result from meteorological satellite imageries, such as FY_2C provided by the National Satellite Meteorological Centre of China (NSMC). Cloud top temperature is used to inverse the rain rate, as they have significant correlation relationship.

Data from GRACE satellites, which measure the variation in the gravity field, are used to estimate the spatio-temporal terrestrial water storage change (TWSC) during the study period (2002–2012). The monthly GRACE gravity field consists of a set of spherical harmonic coefficients. These fields can be then spatially averaged to generate time series of total water storage anomalies [Song, 2015]. After removal of the temporal mean, the GRACE field is filtered using the 300 km wide Gaussian filter method and finally converted to mass in units of equivalent water thickness. Subsequently, these processed spherical harmonic coefficients were transformed into gridded data. The mass variations were then converted to TWSC in units of equivalent water height (EWH). In this study, we use the latest GRACE-Tellus Release-05 gridded Level-3 data of monthly surface mass changes, provided by the Center for Space Research (CSR) at the University of Texas [http://grace.jpl.nasa.gov/data/], which is supported by the NASA MEaSUREs Program. The global TWS data are updated monthly since 2002 and available with 1×1° spatial resolution with the measurement of equivalent water thickness in cm [Wahr, Swenson, 2004]. Atmospheric water storage changes, which have been removed from the signal during the TWS retrieval process, are not considered in this study.

With the measurements on TWS change (TWSC), it is now possible to infer storage of relevant hydrological components, such as glaciers and snow, soil moisture, surface water, groundwater, evaporation, in the water cycle equation. For a given region, TWSC can be expressed as:

$$\frac{dW}{dt} = P - E - R$$

where dW/dT represents the TWSC and the corresponding equivalent water height (EWH).

P represents precipitation, E denotes evapotranspiration (ET), and R represents surface runoff. By integrating GRACE-derived TWSC, hydrological models, and the field-measured data, the changes of TWS components including groundwater, soil water, and ET can be estimated [Jiang *et al.*, 2014].

There are a number of examples of the possible hydrological monitoring applications. In an aridzone, groundwater is one primary source of water for drinking and irrigation. Despite its importance, the way of groundwater recharge and its interactions with surface water largely remains unknown and varies from place to place. As GRACE-derived TWSC provides vertically integrated estimate of the change in total water storage, groundwater estimation becomes feasible with ancillary measurements of surface water and soil moisture. Besides groundwater, soil moisture also plays a crucial role in the water cycle by controlling the partitioning of water and energy fluxes at the land surface and the moisture exchanges at the soil-vegetation-atmosphere interface.

CONCLUSION AND OUTLOOK

Our review suggests that the traditional methodology for the climate change study (e.g. statistical methods and climate models) can be efficiently coupled with remote sensing methods, ecological and hydrological models to explore the climate variations and their influences on the ecosystem over arid regions. The research focus is not only on the better understanding of the climate system and its change over space and time, but also on the ecosystem's responses to such change. Although there exist studies about the climate change, water cycle, vegetation and ecosystems, the majority of them is on the specific aspect only. The interaction between climate and environment, and feedback from ecosystem in response to climate change have rarely been investigated. Large uncertainties and challenges exist for further research over the arid regions.

As for most geographical issues, the spatial scale determines the nature of the research. Different spatial scales can reveal different physical mechanisms of the climate systems and display various characteristics of the ecosystems. The accuracy of datasets are also important. Uncertainties are often found in the gridded climate datasets caused by the insufficient meteorological station data to support the spatial interpolation, or the errors of the climate models themselves [Lioubimtseva, Cole, 2006; Hu *et al*., 2016], or the biases of the remote sensing datasets resulted from cloud and the sensors [Hu *et al.*, 2016]. Therefore, it is essential and requires long-term continuing efforts to overcome the shortfalls for improving the accuracy of the datasets.

Furthermore, it is vital to further enhance data dessimilation and combination methods to match between the point-based field observation data and the gridded datasets (including climate models and remote sensing datasets). In addition, human impacts on the ecosystem may vary environmental variables significantly so that it needs to be estimated and investigated in relation to the scale of issues. The studies about the impacts and consequences of human impacts, such as land use and land cover change and increasing greenhouse gas emission, on the climate change and regional water cycle are urgently needed.

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ГЕОИНФОРМАЦИОННЫЙ АНАЛИЗ ИНДЕКСА БИОЛОГИЧЕСКОЙ ЭФФЕКТИВНОСТИ КЛИМАТА КАК КРИТЕРИЯ ОЦЕНКИ ПОТЕНЦИАЛЬНОЙ УСТОЙЧИВОСТИ ЛАНДШАФТА

АННОТАЦИЯ

В статье рассмотрен индикаторный подход к оценке потенциальной устойчивости ландшафтов. В качестве примера интегрального критерия используется индекс биологической эффективности климата (ТК). Для территории Тверской области выполнены расчёты индекса ТК для оценки устойчивости ландшафтов. Составлены картограммы индекса ТК и его составляющих. Проведен геопространственный анализ и даны оценки потенциальной устойчивости ландшафтов.

Рассмотренный пример картографирования и расчёта индекса ТК может служить отправной точкой для использования в системах многокритериальной оценки состояния и эмерджентных свойств геосистем, построенных на принципах АСПИД-методологии. Данный пример отражает возможность использования индикаторного подхода на первом этапе исследования устойчивости к изменению параметров естественного режима для последующей многокритериальной и интегральной оценки устойчивости к изменению параметров естественного и антропогенного режимов функционирования геосистем.

Использование индекса биологической эффективности климата в качестве индикатора устойчивости позволит активно использовать его в дальнейшем в геоэкологических исследованиях.

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